Experimental Evaluation of Open-Loop Uplink Power Control Using ACTS

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1. Introduction

Satellite communication systems operating in the 20/30 GHz frequency band are subjected to degradations produced by the troposphere that are much more severe compared to those found at lower frequency bands. These impairments include signal absorption by rain, clouds, and gases, and amplitude scintillations arising from refractive index irregularities. For example, rain attenuation at 20 GHz is almost three times that at 11 GHz. Although some of these impairments can be overcome by oversizing the earth station equipment such as antenna and high power amplifier, the current trend of migrating to smaller, low-cost earth stations that can be easily deployed at user premises runs counter to using such brute force methods. As a consequence, most Ka-band systems are expected to employ some form of fade mitigation that can be implemented relatively easily and at modest cost. In this regard NASA's Advanced Communication Technology Satellite (ACTS) which operates in the 20/30 GHz band, provides an excellent opportunity to develop and test such techniques. The present investigation conducted under NASA sponsorship examines the potential of up-link power control as a fade mitigation technique.

Some of the methods applicable for countering rain fading include:

- site diversity
- satellite resource sharing
- up-link power control

Site-diversity takes advantage of finite size of rain cells to enable two earth stations seprated by several tens of kilometers and interconnected via a terrestrial line to provide a continuous link to the satellite. Extra cost of a second earth station and the terrestrial line between them usually make site-diversity a less attractive proposition. Satellite resource sharing involves reallocation of either power or bandwidth to those earth terminals affected by rain. Invariably this increaes the complexity and cost of the satellite. Up-link power control (ULPC) essentially counters fading on the up-link by increasing the power transmitted by the earth station. Other potential candidates for fade mitigation include orbital diversity and selective use of lower frequncy channels.

Up-link power control can be implemented in several forms, including:

- open-loop
- closed-loop
- feedback-loop

The open-loop scheme relies on estimating the up-link fade by independent means such as monitoring a satellite borne beacon signal or radiometry. In closed-loop implementations, the transmitting earth station uses its own transponded carrier to estimate the up-link fade. With feedback-loop, a central control station commands each earth staion in the network to adjust its power to compensate for fading on its own up-link. In terms of implementation complexity open-loop is the least complex since it can be deployed at an earth station without any systemwide considerations. Closed-loop control is not always realizable since the availability of the transponded carrier depends on the network configuration. Feedback-loop control is more complex requiring systemwide considerations and additional resources, both on the ground and on the spacecraft.

Power control accuracy is a major concern for systems prone to adajacent channel interferences. In addition, transmission of exececssive power can cuase harm to the spacesegment and to adjacent satellites. Closed-looop and feedback-loop power control systems can provide superior power control accuracy. In the case of open-loop systems, accuracies akin to the other two systems may be obtained using a beacon signal close to the transmit frequency to estimate the up-link fade. Mainly spurred by this requirement, a frequency allocation for an up-link beacon for Ka-band satellite systems was instituted by the World Adminstattive Radio Conference in 1992. However, reception of a weak beacon signal which lies close to a strong transmitting signal poses few problems. Although these can be surmounted easily, the additional investment required for a complex feed system and a receiver operating in a frequency band different from the down-link can be a burden on VSAT type applications where end-user cost is a major concern. Instead of using an up-link frequncy beacon, a beacon signal within the down-link frequency band can be used to estimate the fading on the up-link. This method is less accurate since fading on up- and down-link are not highly correlated. However, through careful considerations of propagtion factors involved in the fading process, acceptable accuracy levels may be achieved.

The present investigation deals with the implementation of open-loop up-link power control using a beacon signal in the down-link frequency band as the control parameter. A power control system was developed and tested using the ACTS satellite. ACTS carries beacon signals in both up- and down-link bands with which the relationship between the up- and down-link fading can be established. A power controlled carrier was transmitted to the ACTS satellite from a NASA operated ground sataion and the transponded signal was receieved at COMSAT Laborotories using a terminal that was routinely used to monitor the two ACTS beacon signals. The experiment ran for a period of approximately six months and the collected data were used to evaluate the performance of the power control system.

A breif review of propagation factors involved in estimating the up-link fade using a beacon signal in the down-link band are presented in Section 2. Section 3 describes the power controller design and the experiment configuration. Results of the experiment are discussed in Section 4.

2. Propagation Considerations

Propagation factors that have an impact on the design of Ka-band open-loop up-link power control systems that use a down-link signal to infer the up-link fade include:

- gaseous absorbtion
- cloud and rain attenuation
- tropospheric scintillations

The detected down-link fade is a combination of these factors. The power controller has to translate the down-link fade to the up-link using frequency sacling ratios applicable for each of the above factors. In general, the frequency scaling ratios for different propagation phenomena are not the same. Within the 20/30 GHz frequency band the gaseous absorption follows a complex frequency scaling law which is a function of the atmospheric water vapor content. For rain and clods the fade ratio can be approximated by $(f_1/f_2)^2$, where f_1 and f_2 are the frequencies at which fades are measured, and for topospheric scintillations the scaling ratio has the form $(f_1/f_2)^{7/12}$[1]. It is generally not feasible to seperate the absorptive components (gases, clouds, and rain) from each other; however, the non absoptive tropospheric scintillations can be separated from absorptive components using filtering techniques[2]. Since rain attenuation is the main factor a power control system has to contend with, the frequency sacling ratio for rain is of primary importance for the contoller design. The frequency scaling behaviour of rain attenuation is essentially a function of the rain type (stratiform, thunderstorm etc.); in addition, it can vary considerably during a single rain event. Figure 1 shows the frequency scaling ratio between 20 and 27 GHz fades observed during a summer rain event at a site in Clarksburg, MD; Fig. 1a shows the fade levels observed on the 20 and 27 GHz ACTS beacons, Fig. 1b shows the fade ratio as a function of the 20 GHz fade, and Fig. 1c shows the time series of the fade ratio. At low fade levels (<3 dB) the fade ratio is essentially determined by the gaseous absorption; Fig 1b also shows the combined effect of gaseous absorption and rain attenuation as predicted by theory. It is evident that considerable variation in the fade rato exist at high fade levels where rain fade is the dominant factor.

Figure 2a shows the distribution of the instantaneous frequency scaling ratio between 20 and 27 GHz fades coressponding to an observation period of 12 months; Fig. 2b shows the fade ratio on an equiprobable basis for the same observation period. Based on the instantaneous values, it is seen that for fades larger than about 3 dB the mean frequency scaling ratio is of the order of 1.8 dB. The equiprobable ratio has a similar magnitude. The distrbution of the instenteneous ratio around the mean is such that 90% of the values are contained within approximately ±10% of the mean value. This imples that the use of a constant frequency scaling ratio will limit the power control accuracy to approximately 10% of the fade level being compensated. The alternative of using a variable frequency scaling ratio which must adapt to the prevailing rain conditions is rather complex and may require additional information on the rain process. The experiment described in the next section was designed to evaluate power control error bounds resulting from the use of fixed frequency sclaing ratios.

3. Experiment Description

In order to evaluate the effectiveness of open-loop power control for Ka-band applications, a power control system was designed and fabricated. Figure 3 shows the main components of the control system. The control functions are carried out by a board level computer based on an Intel-80386 processor. The main input signal to the control system is the down-link beacon signal which is sampled at a rate of approximately 5 Hz. The computer processor first estimates the down-link fade and then translates it the up-link frequency. The power control is applied through a PIN diode attenuator placed in the signal path at an intermediate frequncy (IF) stage. Several safety features and alarm circuits are built into the system to prevent excessive power being transmitted towards the satellite. In case of an alarm a safety relay is activated and the power controller becomes transparent to the incoming signal.

The basic building blocks of the power control algorithm are shown in Figure 4. The incoming beacon signal samples are first used to obtain an estimate of carrier-to-noise ratio (C/N) over an averaging interval of 2 min. Next, the beacon level is separated into a clear sky reference level and a propagation contribution. The clear sky reference is the beacon level that would have been measured if negligible amounts of propagation impairments were present. The reference level is determined by drifts in the earth station receiver and thermal effects at the satellite. As a consequence, the clear-sky level esentially follows a diurnal pattern. The propagation contribution extracted after removing the clear-sky level is further divided into rain fade and signal scintillations. The frequency scaling laws applicable to rain and scintillation are applied to these components. The resulting values are added together to obtain the up-link fade level. The transmit power is then adjusted to compensate for the up-link fade.

The identification of the clear sky level is based on a filtering process in which relatively slow variations induced by the equipment are separated from somewhat faster varying propagation effects. This division is not always a clear-cut one. Slow propagation induced variations such as cloud attenuation and water vapor absorption cannot be factored out easily. Provided these effects are relatively small (< 1 dB), they can be lumped together with equipment effects without adversely affecting the control accuracy. On the other hand, complete isolation of propagation activity from equipment induced variations can be achieved by knowing the system noise temperature and determining the C/N to a high degree of accuracy. The extra effort required, however, is not commensurate with the resulting gain in link performance at such low levels of propagation activity. Variations in the C/N estimate over a two minute averaging period together with the slope of the beacon level are used for identifying the clear sky level. If the estimates are found to be within pre-set limits, the corresponing mean value of the beacon level is used to construct the clear-sky baseline; otherwise the base-line level is estimated from the previous clear-sky estimates using a predictive algorithm. The prediction makes use of samples collected during the previous two hours (60 samples). During rain fade events that last over several hours, the baseline predictive algorithm may not perform adequately. Under such circumstances, the baseline level from the previous day has a dominant influence on the current baseline estimate.

Once the baseline is established, any variation around this level is assumed to be induced by propagation phenomena. Two types of propagation factors are accounted for by the algorithm: fading caused by rain and heavy clouds and tropospheric scintillations. The two types can co-exist and they need to be separated before determining their contributions to the up-link. Scintillations are fast variations in signal level induced by tropospheric refractive irregularities. Variations are largely symmetrical about a mean level and fluctuations are restricted to frequencies above about 0.5 Hz. A running average of the estimated fade level, taken over a 20 second interval, appears to be sufficient to remove almost all scintillation effects. A delay of 10 seconds is introduced by the 20 seconds averaging filter. Therefore, to obtain the current rain fade level, a predictor similar to the one used for the baseline level is used. The predictor is based on maximum entropy[3] and can be applied to non-stationary processes such as rain.

After separating the rain and scintillation components, frequency scaling laws are applied to the two components. The up-link rain attenuation, A_{uR} can be approximated by:

$$A_{uR} = A_{dR} (f_u/f_d)^2 \quad \text{(dB)} \qquad [1]$$

where A_{dR} is the down-link rain attenuation, and f_u and f_d are the up- and down-link frequencies, respectively. The factor involved in the scaling of 20 GHz fade to 27 GHz is 1.85. The measured fade ratio shown in Fig. 2 includes the effects of gaseous absorption and scintillations, and therefore, somewhat smaller compared to the ratio for rain alone.

For tropospheric scintillation, the scaling law employed is:

$$S_u = S_d (f_u/f_d)^{7/12} \quad \text{(dB)} \qquad [2]$$

where S_u and S_d are the scintillation levels at the up- and down-link frequencies.

The up-link signal level, L_u, is given by:

$$L_u = A_{uR} + S_u \qquad [3]$$

In these calculations all quantities are in logarithmic scale (dBs).

In order to evaluate the performance of the power control system developed, a long-term test using the ACTS satellite was conducted. The test involved transmitting a power controlled carrier from the NASA ACTS ground station in Cleveland to the ACTS satellite and receiving the transponded carrier at an earth station in Clarksburg. Figure 5 shows the basic experiment configuration. The satellite was configured in the microwave switch matrix mode (MSM) and the E-08 spot beam of the satellite was used to beam the pilot signal towards Clarksburg. Starting from May, 1994, the experiment ran for a period of about 6 months. The power control evaluation was one of many experiments conducted using the satellite, and the actual satellite time used for the experiment was approximately 350 hours. During the test period several rain events were encountered and these were deemed sufficient to evaluate the controller performance. In addition, off-line evaluation of the system was carried out using beacon data collected at Clarksburg.

At the transmit site in Cleveland, where the elevation angle to the ACTS satellite is 39°, the ACTS beacon signals are received via the 3.5 m NASA Ground Station (NGS) antenna using the beacon measurement system (BMS). The 20 GHz beacon signal is used by the power controller unit to estimate the down-link fade. The power controlled carrier at 70 MHz was derived from a signal synthesizer and fed to the power controller. The power controlled carrier coming out of the controller was fed to an up-converter that translates the 70 MHz input to an L-band frequency suitable for feeding the transmit chain of the Link Evaluation Terminal (LET); the transmit frequency was 29.5 GHz. The power amplifier of the LET saturates at an input of approximately 30 dBm. The nominal output of the power controller is maintained at a level close to 0 dBm, giving a total power control range in excess of 30 dB. The separation between the NGS antenna and the LET antenna is about 15 feet. Because of this, some decorrelation between fading on the up- and down-link was observed. However, the impact of the antenna separation on the general outcome of the experiment was thought insignificant.

At the receive site the antenna used was a 1.2 m offset reflector which can receive both the beacons, the pilot carrier at 20.3 GHz, and sky noise at 20 and 27 GHz. Beacon signals were received with a receiver detection bandwidth of 65 Hz; the pilot carrier detection bandwidth was 400 Hz. Clear-sky signal to noise ratio for the beacon channel was 33 dB; that for the pilot signal was 35 dB. The 20 GHz beacon level was used to remove any propagation induced variations occurring on the down-link leg of the pilot carrier thus enabling to estimate the received pilot levelat the satellite. In addition to the beacon signals and skynoise levels, several meteorological parameters are recorded in this data logger; these are rain intensity, humidity, and wind speed.

4. Results

Use of a narrow-band carrier signal allowed the power controller to be operated with a maximum fade compensation range of 25 dB. In operational systems the usable power control range would normally be much smaller. In view of this, results and analysis presented in this section pertain to a fade control range of 15 dB. During the entire experiment period the power controller was operated with the same configuration.

The collected data from the two sites were analyzed to evaluate the performance of the power controller unit. This required the extraction of fade depths from recorded signal levels. One of the difficulties encountered during this process was the lack of absolute levels to obtain precise fade levels. Session to session variations in received power levels could not be accurately defined. In addition, level variations caused by the slow drift of the spot beam pointed towards the Clarksburg site could not be removed completely. The overall uncertainity due to these error sources is of the order of 0.5 dB.

Clear-sky conditions were investigated to examine the degree to which the controller was able track out equipment effects as well as slowly varying propagation effects. Fading conditions were investigated through analysis of individual rain events as well as statistical analysis of the control error. In addition, an off-line analysis of the power control algorithm was conducted using beacon signal data collected with the Clarksburg propagation measurement terminal.

Under clear-sky conditions the power controller is expected to remove slow variations in the beacon level caused by thermal effects and minor propagation contributions that includes gaseous absorption and light cloud situations. Figure 6 shows a 12 hour period during which only low-level propagation activity was present at the transmit site in Cleveland (maximum up-link fade around 2 dB). The two beacon levels and the up-link fade estimated by the power controller (EIRP with respect to nominal) are shown. It is seen that the power controller was adjusting the baseline in response to slow variations in the 20 GHz beacon level. This was due to the fact that the original software used in the controller did not use adequate sampling to estimate the C/N and proper thresholds in the detection of slow fades, especially under conditions of signal scintillations. An additional flaw in the software was that the baseline level was allowed to drift below the average beacon level, thus producing small amounts of undercompensataion. However, these shortcomings were found to be rather benign, and in most cases the errors were contained within about ±1 dB. The periodic pulses on the 20 GHz beacon channel are produced by ranging tones and the power controller reacts to them assuming the pulses are caused by propagation activity. The pulse amplitude is around 0.4 dB, and this was considered insignificant to be corrected by the control software. The negative going narrow pulses of approximately 4 dB appearing on the EIRP channel are the synchronization pulses inserted every hour to enable synchronization of data files generated at the two sites.

The power control error can be depicted in one of two forms: received pilot level at Clarksburg or the difference between the 27 GHz beacon fade and the predicted up-link fade at Cleveland. The pilot level at Clarksburg indicates how well the power controller managed to maintain the power at the satellite close to the nominal level; the down-link propagation effects on the pilot must be removed using the 20 GHz beacon. Since the transmit and receive antennas at Cleveland were not identical, the pilot level does not give a true measure of the power control error. The main objective of the pilot measurement was to evaluate the power controller behavior under operational conditions. On the other hand, the difference between the predicted and the measured fade at the transmit site can be considered a better indicator of the power control error. However, the frequency for which the up-link fade is predicted is 2.1 GHz away from the beacon frequency of 27.5 GHz, and the differential attenuation between the two frequencies can affect the control error estimate. The differential attenuation can be as much as 2 dB at fade levels closer to 15 dB.

Figure 7a shows a rain event recorded at Cleveland; fade levels at 20 and 27 GHz together with the up-link fade predicted by the power controller are shown. The up- and down-link fades were estimated by taking the clear-sky levels before and after the event, and therefore, do not include contributions from gaseous absorption. The event lasted about 30 minutes and the up-link fade exceeded the 25 dB level for more than two minutes. The transmit EIRP plot clearly shows that the power controller was tracking out the gaseous absorption component. Figure 7b depicts the power control error in terms of the pilot level received at Clarksburg as well as the difference between the 27.5 GHz fade and the predicted up-link fade at Cleveland. The control error is blanked out for periods during which the controller was predicting fades in excess of 15 dB. The under compensated area starting around the 45 min. mark was the result of the controller reacting to a modulation pulse. The effect is compounded by the fact that the control error was derived after subtracting the 20 GHz beacon level.

The two error curves shown in Fig. 6-5b do not track each other very well due to somewhat differing propagation conditions in front of the transmit (LET) and receive (NGS) antennas at Cleveland. As an example, the period in between the two attenuation peaks show opposite behavior; fading on the LET antenna appears to be smaller than that on the NGS antenna. However, the overall appearance of the two error plots, both in terms the maximum value and the average value, are quite similar. This suggests that, from a statistical point of view, the separation between the antennas did not have any significant impact on the error estimate. Although the antenna separation of approximately 15' is sufficient to have complete decorrelation of scintillation, to a large extent, rain fading can be considered correlated.

A second rain event recorded at Cleveland is shown in Figure 8. The event consisting of three distinct peaks lasted approximately one hour. The first peak caused the 20 GHz beacon to lose lock, and as a consequence, the power controller was unable to recover from the fade correctly. It is also seen that the onset of the third peak at the two antennas occurred at different times.

Rapid rise and fall of deep fades makes it difficult to follow them accurately, and this is clearly evident in control error plots. During both events the power controller was able to maintain the control error within about ±2.5 dB, except during the recovery of the 20 GHz beacon from loss of lock.

Performance of a power control system may be evaluated at least on two criteria: overall improvement to link availability, and control error at the satellite. The overall improvement to the link availability requires continuous measurements spanning a minimum period of one year to account for seasonal differences in precipitation and scinitillation activity. This information may be obtainable through an analysis of the long-term beacon data collected with the Clarksburg propagation terminal. Evaluation based on the control error should also be carried out using long-term measurements or post processing of long-term propagation data. However, the control error can be considered less sensitive to seasonal variations, and therefore the error statistics obtained from to the limited set of measurements can still be considered representative.

Error statistics generated for the duration of the experiment are shown in Figure 9; the control error for several exceedance probabilities ranging from 1% to 99% are plotted against the up-link fade. Statistics shown pertains to all rain events observed at the Cleveland site and the control error was derived from the fade on the up-link beacon and the pilot carrier output of the power controller. To account for the frequency difference between the pilot carrier and the up-link beacon, a correction of 1 dB was applied to carrier levels in excess of 10 dB. It is seen that the control error increases with the up-link fade. This is partly due to the increase of differential attenuation between the pilot and the up-link beacon, which was only partially compensated by the above mentioned correction. By applying full compensation for the frequency difference (i.e. correction of approximately 2 dB at 15 dB of up-link fade), the control error may be limited to ±2.5 dB instead of ±3.5 dB shown in the figure. With the increase of the up-link fade the spread of the error tend to increases as well. The lower bound of the control error is largely determined by the uncertainty in baseline estimation. Since the control algorithm used during the measurements was not optimized, the spread appears to be overly large. Errors in the signal enhancement region (negative fades) are dominated by those arising from modulation pulses. The power output from the controller was below the nominal level for the entire duration of the pulse thus producing a negative control error.

5. Conclusions

In this work a detailed study of issues pertaining to the design and operation of open-loop up-link power control for Ka-band applications was undertaken[5]. The ACTS satellite and the NASA ground station facilities in Cleveland, OH, were instrumental in the successful conduct of the investigation. Rain impairment amelioration techniques which can be implemented at modest cost are expected to play a pivotal role in commercial exploitation of the 20/30 GHz frequency band. The investigation proved that power control, even when implemented as an open-loop system, is quite effective in combating rain fading. Open-loop power control can be made more robust by using a beacon signal closer to the up-link frequency band; regulatory provision for such beacons in future Ka-band satellite systems has been mandated. However, the power controller was designed around a beacon signal in the down-link band as a way of keeping the system cost to a minimum.

Spurred by the same cost consideration, a design based on IF control was selected. The alternative of using RF control entails the use of expensive RF components as well as operational complexities. One of the advantages of RF control is that it allows for multi-carrier operation in large earth stations. However, the present design can be easily adapted for multi-carrier operation by incorporating additional IF stages driven by a single master controller. This will add only a small incremental cost to the power control system.

In the evaluation of the design, the same control algorithm was used from the beginning to the end of the experiment period. Data analysis at the end of the period reveled several shortcomings of the algorithm. However, these did not have a major impact on the power controller performance during the two dozen or so rain events observed at the transmit site. Although the experimental setup used for the investigation was less than ideal, the data collected allowed the assessment of the performance bounds of the controller.

The rain events encountered during the experiment period were mainly of summer thunderstorm type with durations averaging between 0.5 to 1 hour. On-line evaluation of the controller under lingering rain, which can last several hours, could not be accomplished. However, off-line analyses have indicated that the event duration did not affect the controller performance significantly.

The investigation was limited to a power control range of 18 dB (15 dB of fading and 3 dB of enhancement). This level of control was thought to represent an upper bound on the power control ability of most commercial systems. In general, the power control system was capable of regulating the EIRP within ±2.5 dB over the selected range. It was determined that the clear-sky power control uncertainty can be further reduced through careful selection of the control parameters. At the high end of the fade range the control error is due to the combined effects of the controllers inability to follow deep fades and the hysterisis in fade scaling ratio normally observed with deep fade events. Reduction of the error at this error may be attempted through refinements to the control algorithm. One such refinement could be an implementation based on estimating the short-term fade rates and adapting the fade prediction accordingly. Use of a frequency scaling ratio sensitive to the fade depth would also help reduce the control error.

The range of power compensation applied is essentially a function of the desired link availability and the associated earth station equipment cost. Up to the selected upper bound, performance of the controller is not very sensitive to the control range. As a result the decision as to what level of compensation should be applied can be made solely on the basis of the service type and other aspects of the satellite network.

6. References

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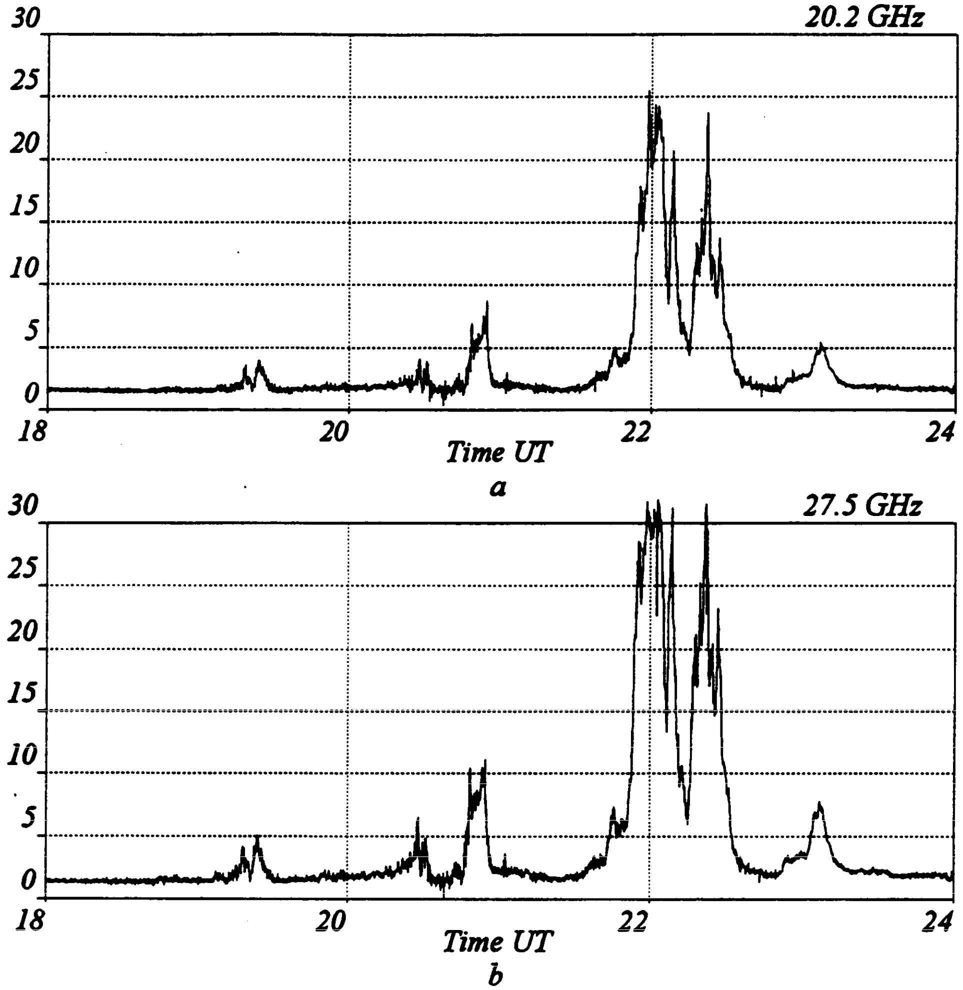


Figure 1a,b Attenuation at 20 and 27 GHz; Rain Event on 14 August, 1994

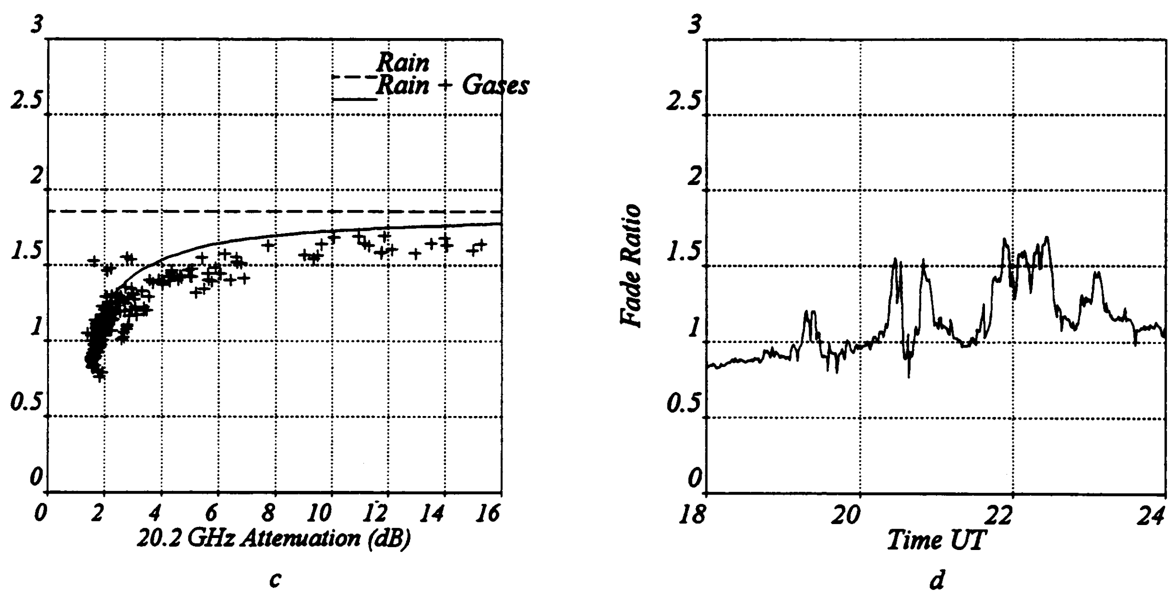


Figure 1c,d Ratio between 27 and 20 GHz Fades; Rain Event on 14 August, 1994

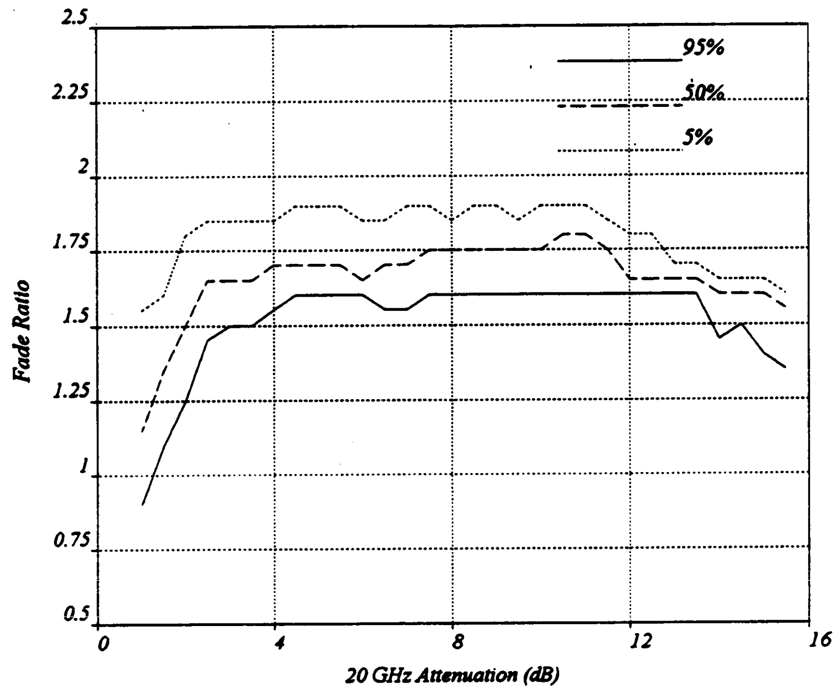


Figure 2a Distribution of Instantaneous Fade Ratio Between 27 and 20 GHz

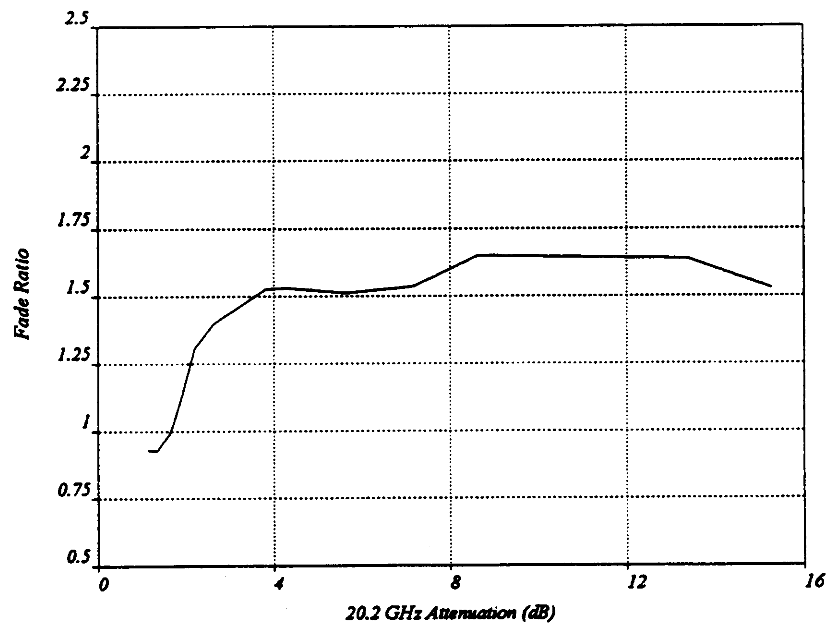


Figure 2b Equiprobable Fade Ratio Between 27 and 20 GHz

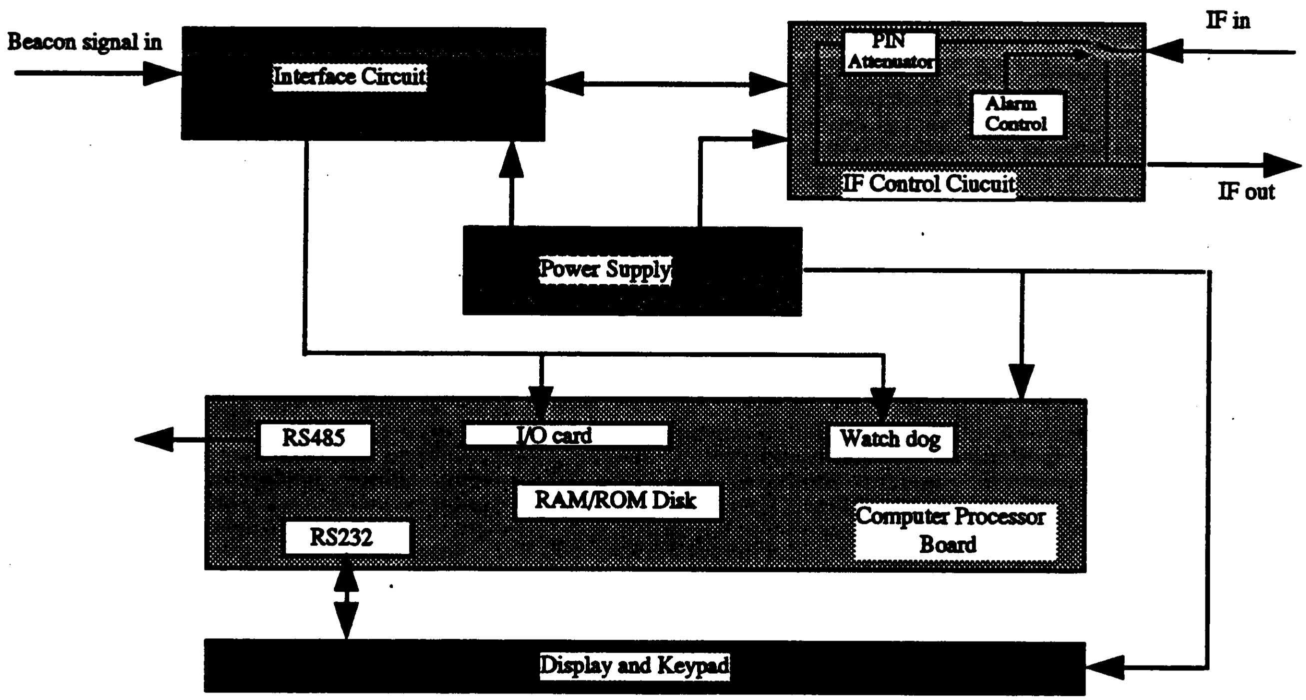


Figure 3 Functional Block Diagram of the Up-link Power Controller

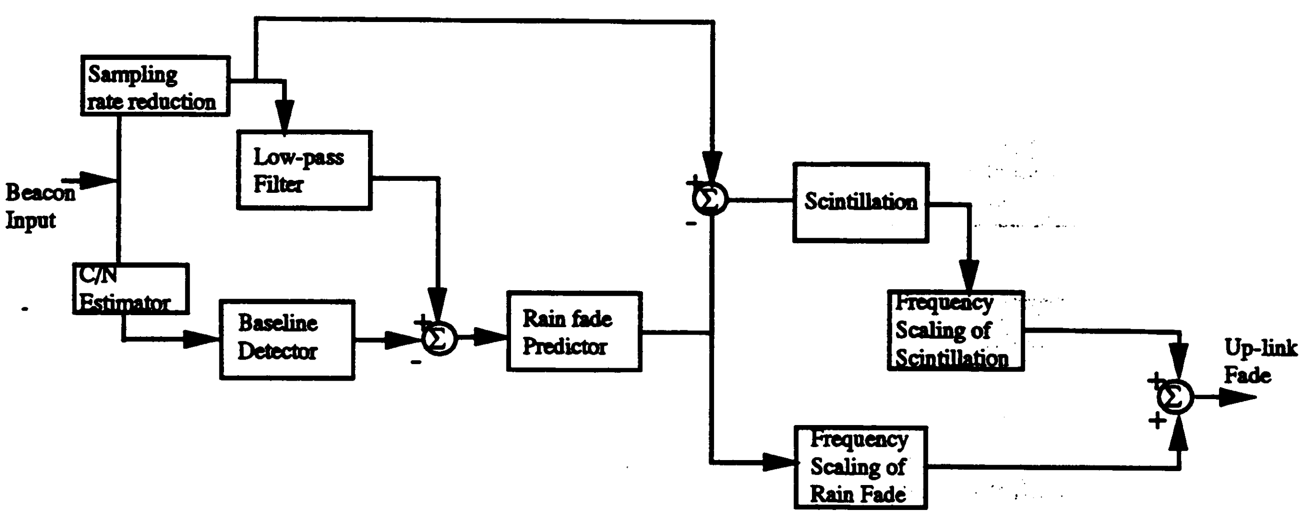


Figure 4 Up-link Fade Estimation Algorithm

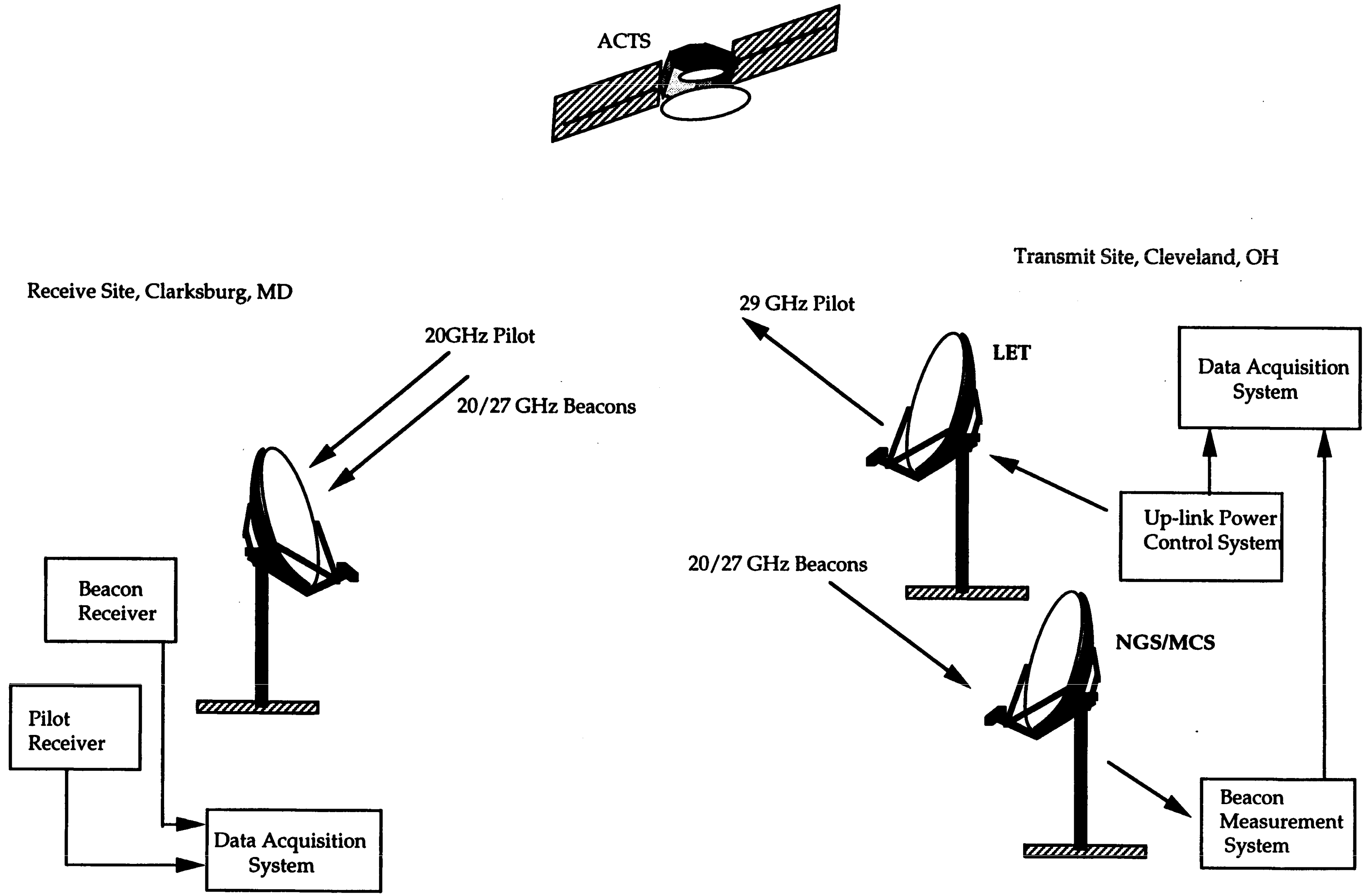
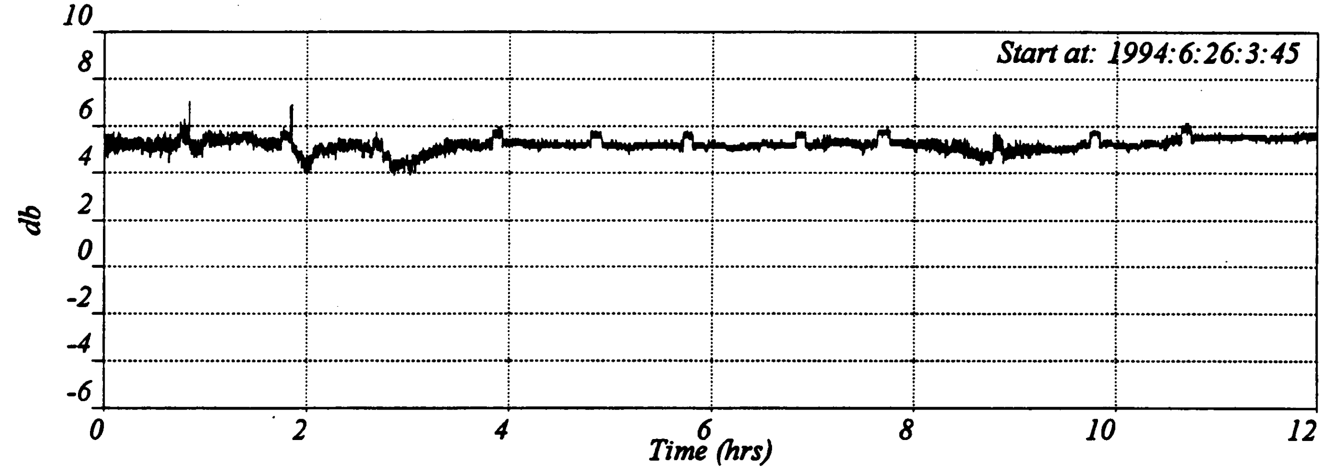
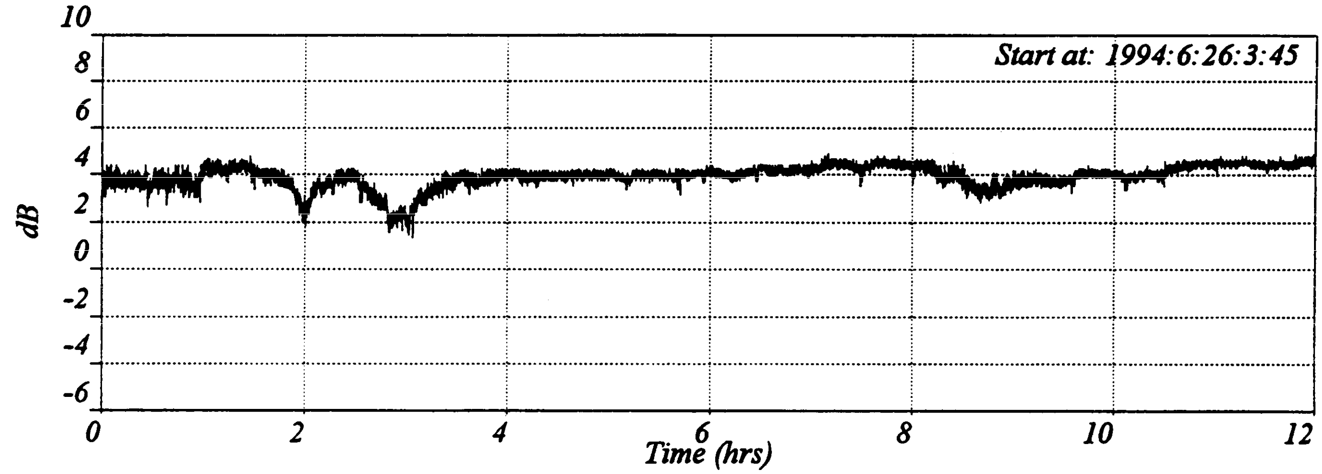


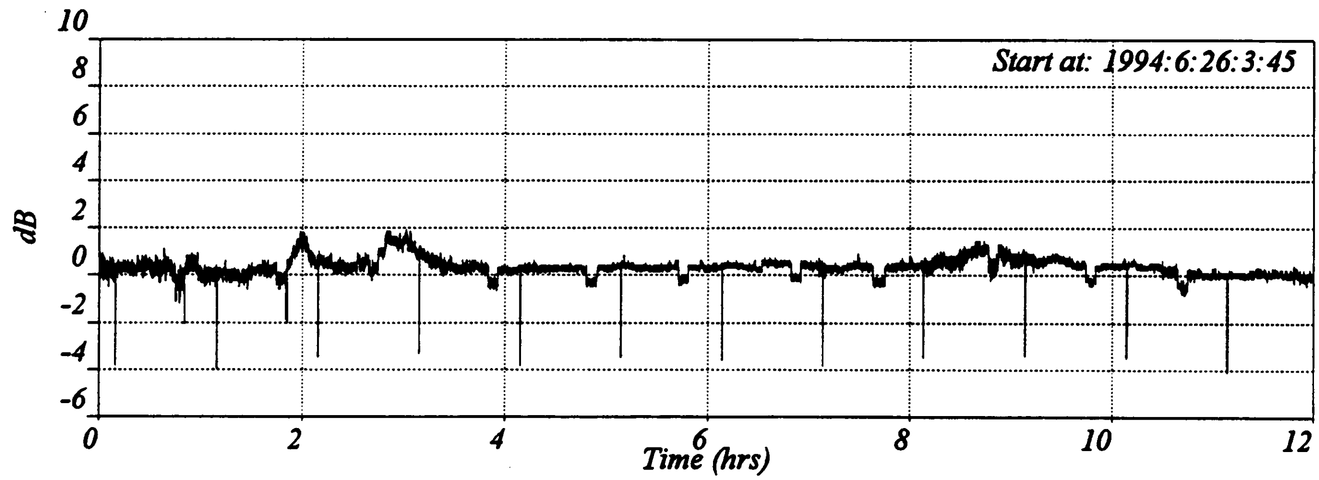
Figure 5 ACTS Up-link Power Control Experiment Configuration



20.2 GHz Beacon Level

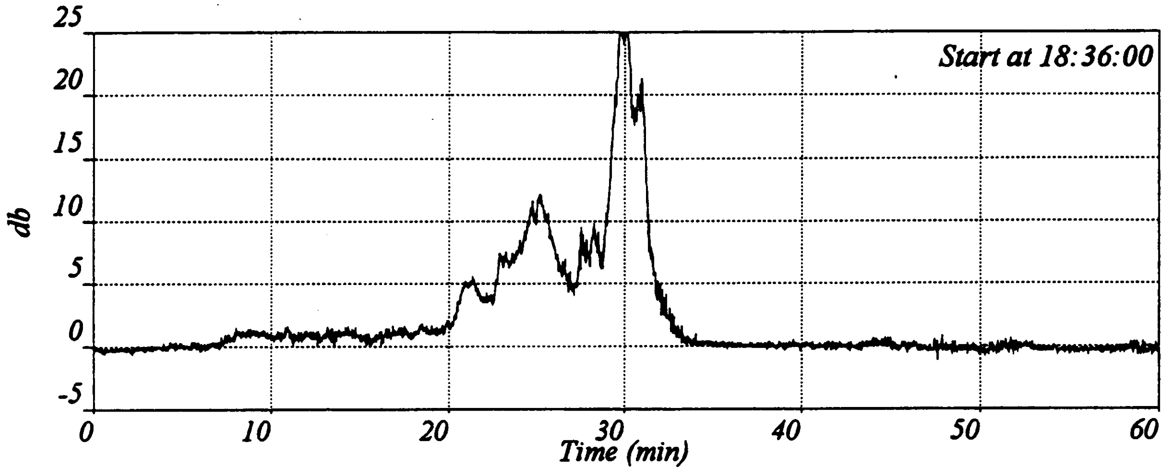


27.5 GHz Beacon Level

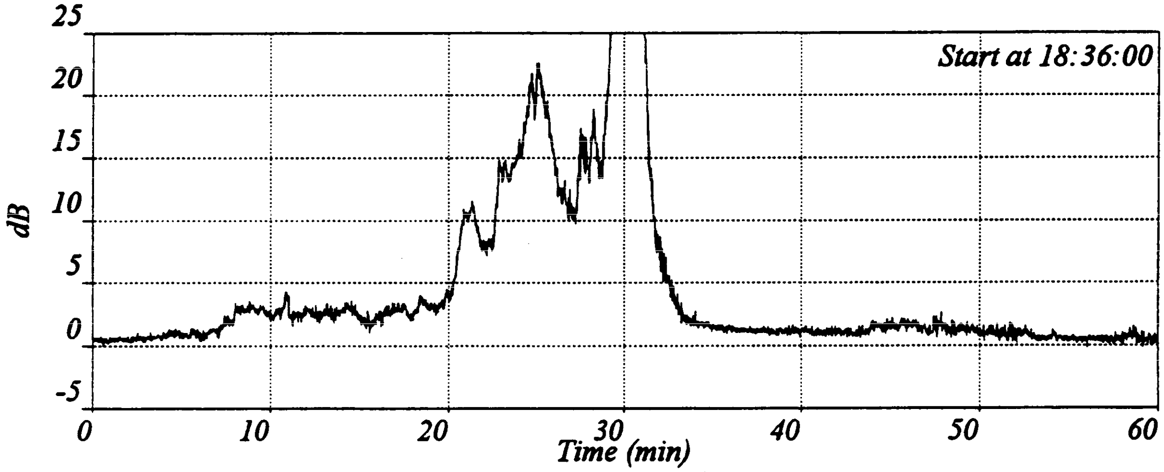


Transmit EIRP Relative to Nominal

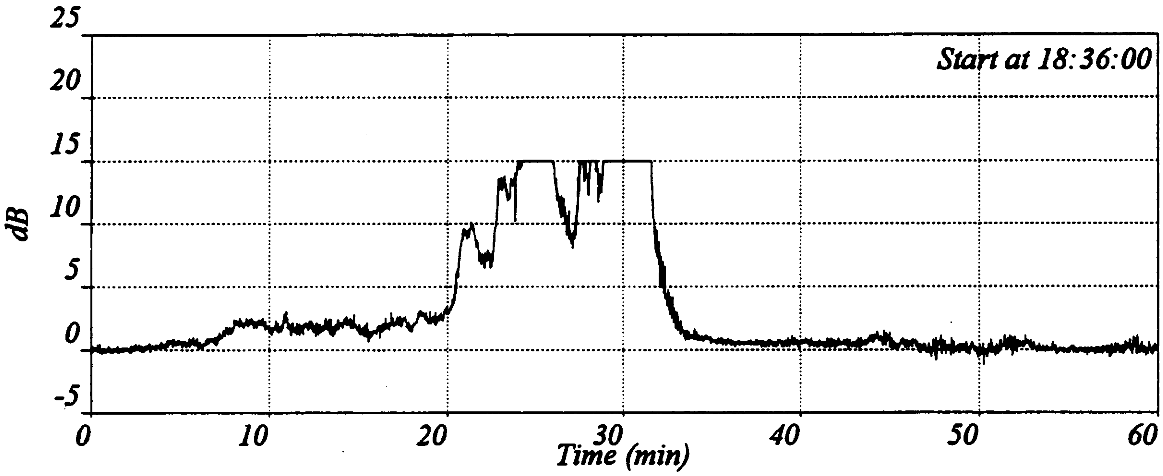
Figure 6 Clear-sky Performance of Power Controller



20.2 GHz Fade

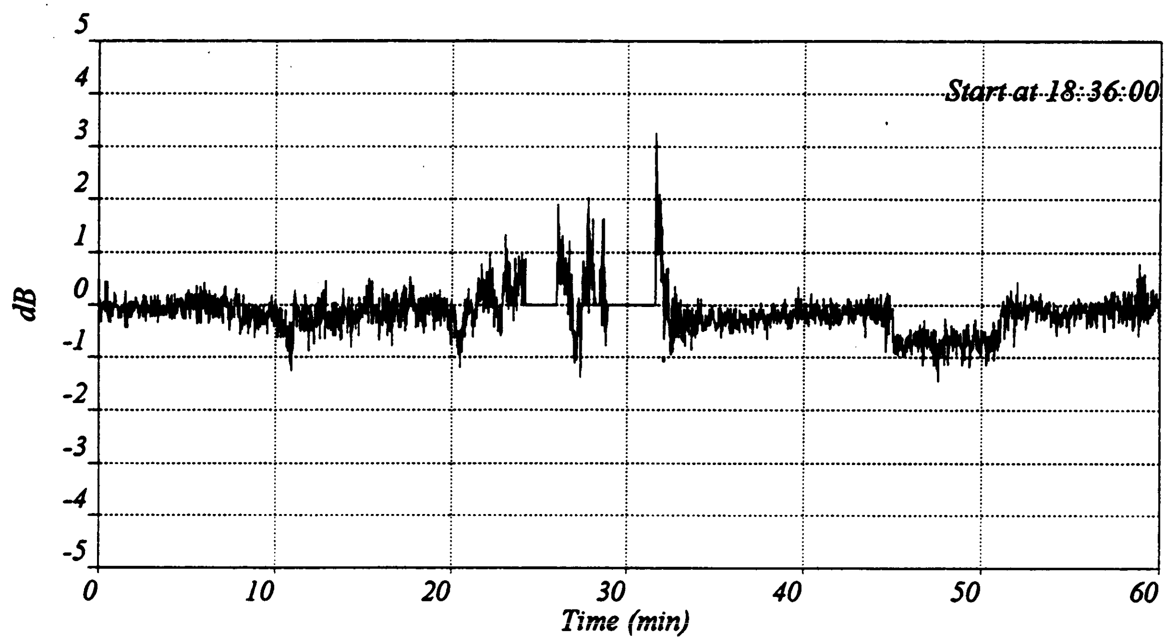


27.5 GHz Fade

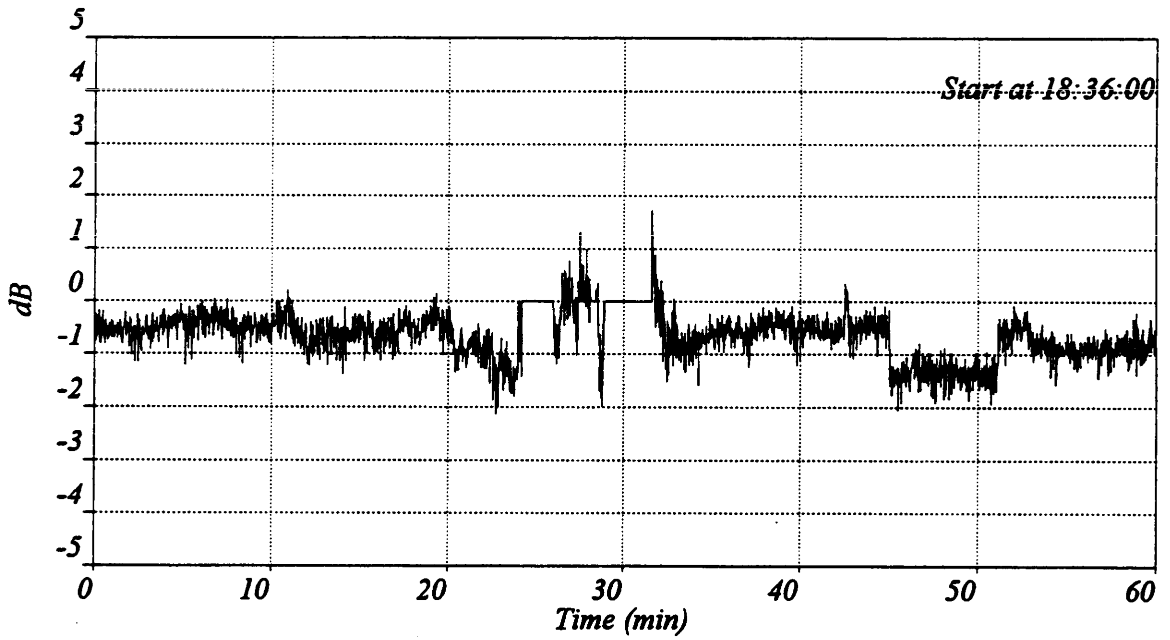


Estimated Up-link Fade

Figure 7a Rain Event 1 on 31 May, 1994

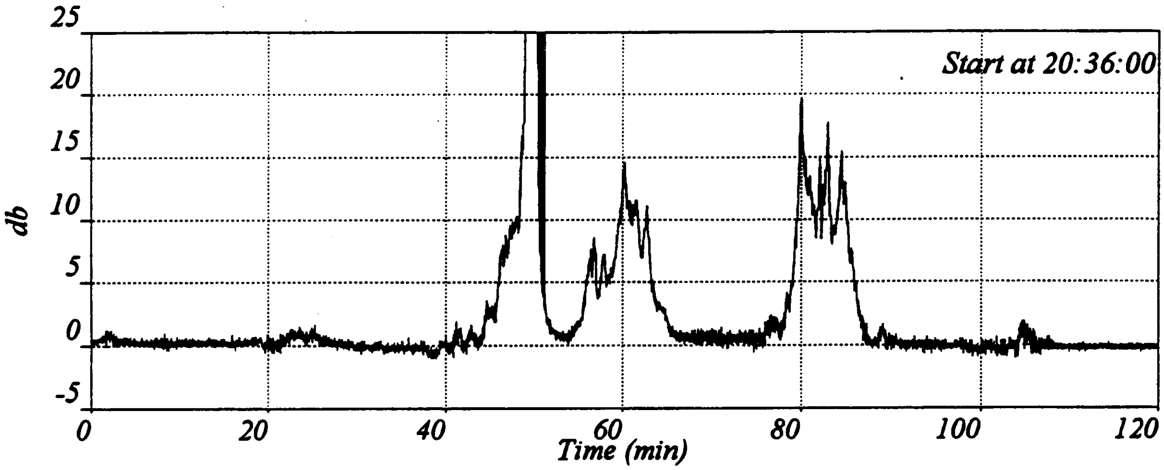


Control Error at Cleveland

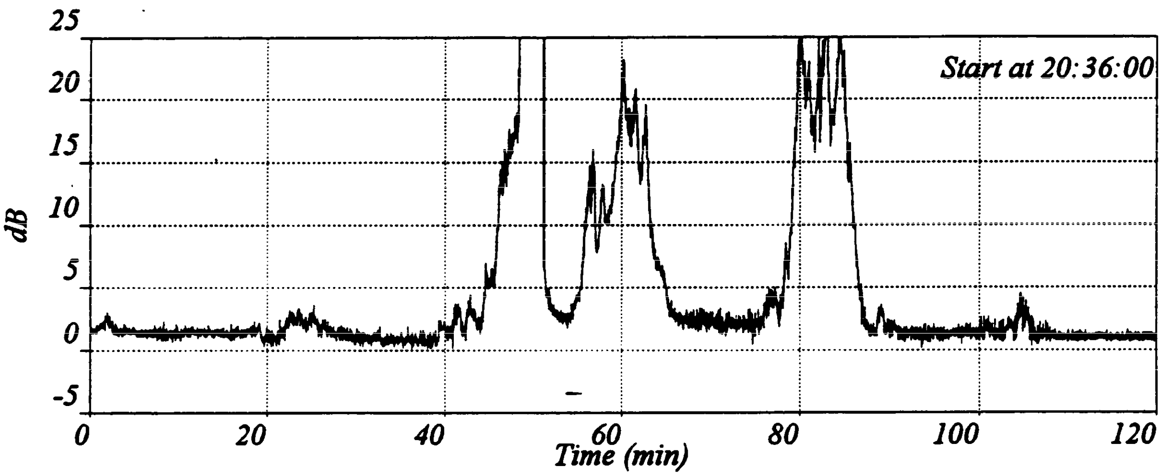


Pilot Level at Clarksburg

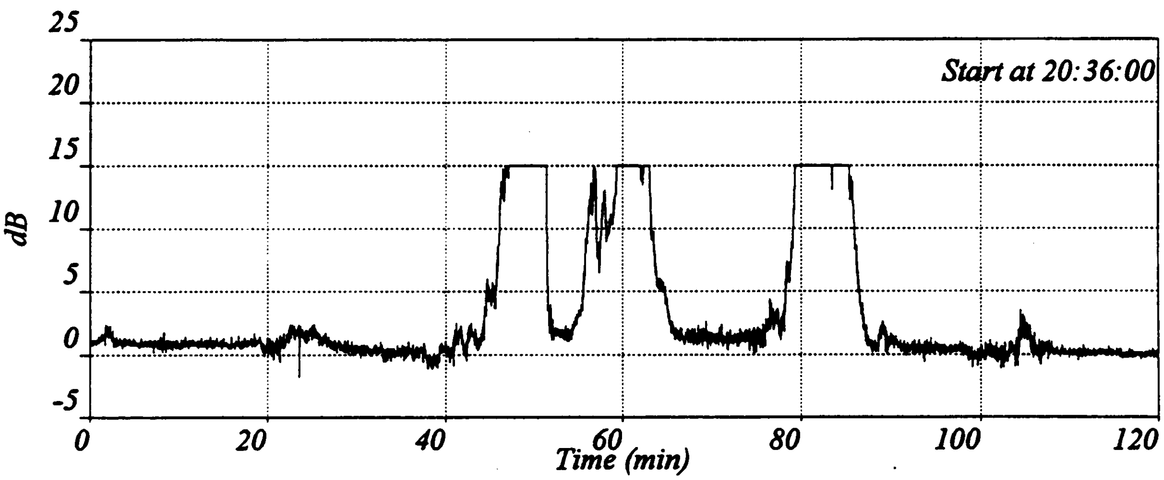
Figure 7b Control Error; Rain Event 1; May 31, 1994



20.2 GHz Fade

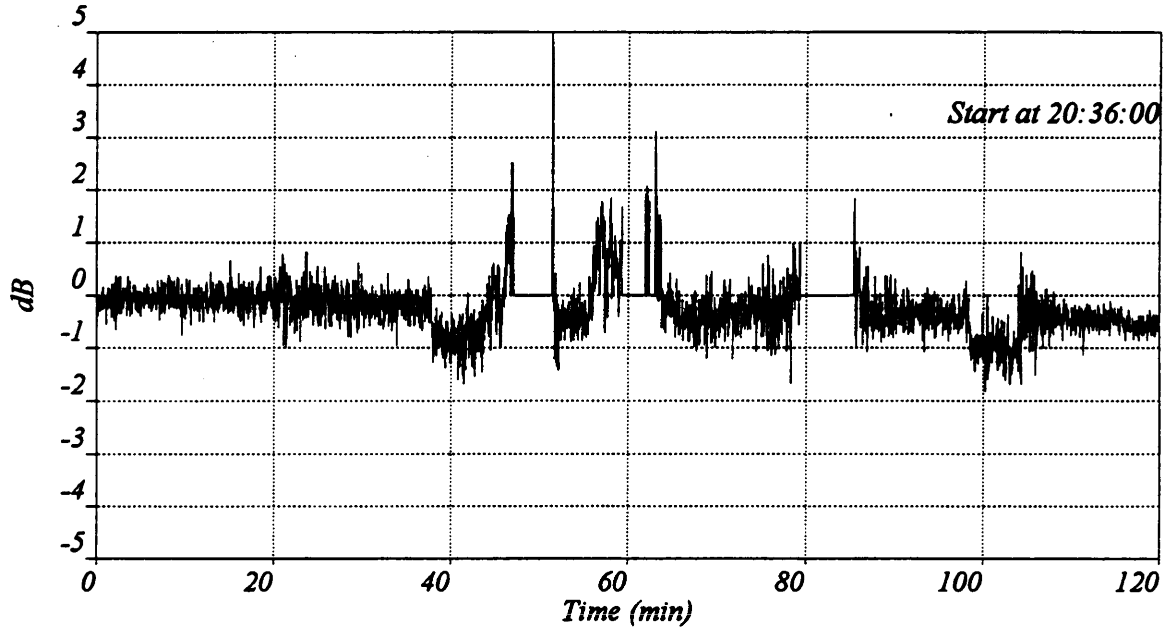


27.5 GHz Fade

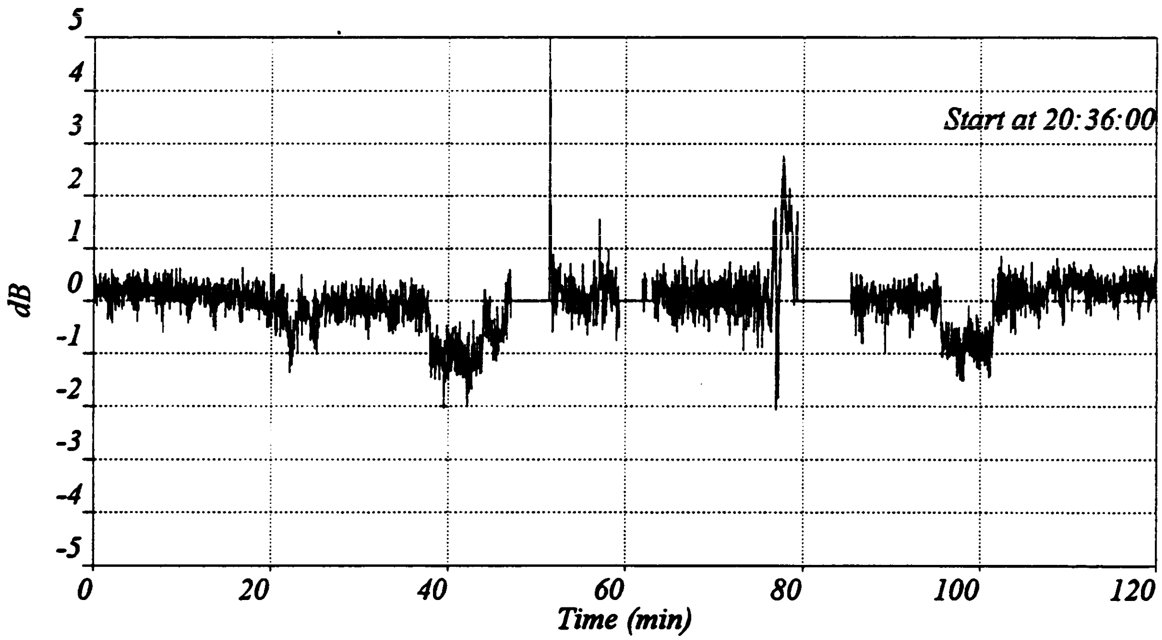


Estimated Up-link Fade

Figure 8a Rain Event 2 on 31 May, 1994



Control Error at Cleveland



Pilot Level at Clarksburg

Figure 8b Control Error; Rain Event 2; May 31, 1994

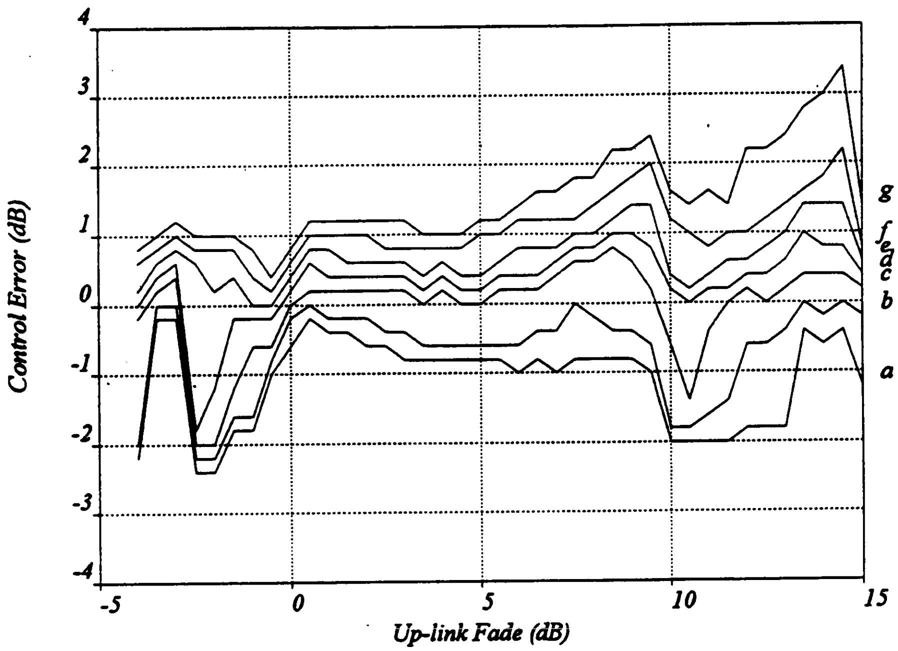


Figure 9 Distribution of Power Control Error;

a: 99%, b: 95%, c: 75%, d: 50%, e: 25%, f: 5%, g: 1%